Physics Of Failure for Complex Systems

Manufacturing Technologies for Integrating

Nano-to-Millimeter Sized Systems

—The State-of-the-Art, and Opportunities for Further Advances —

DARPA/NIST Workshop

March 11-12, 1999

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Electronics Reliability Prediction History

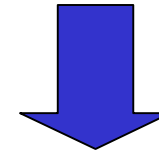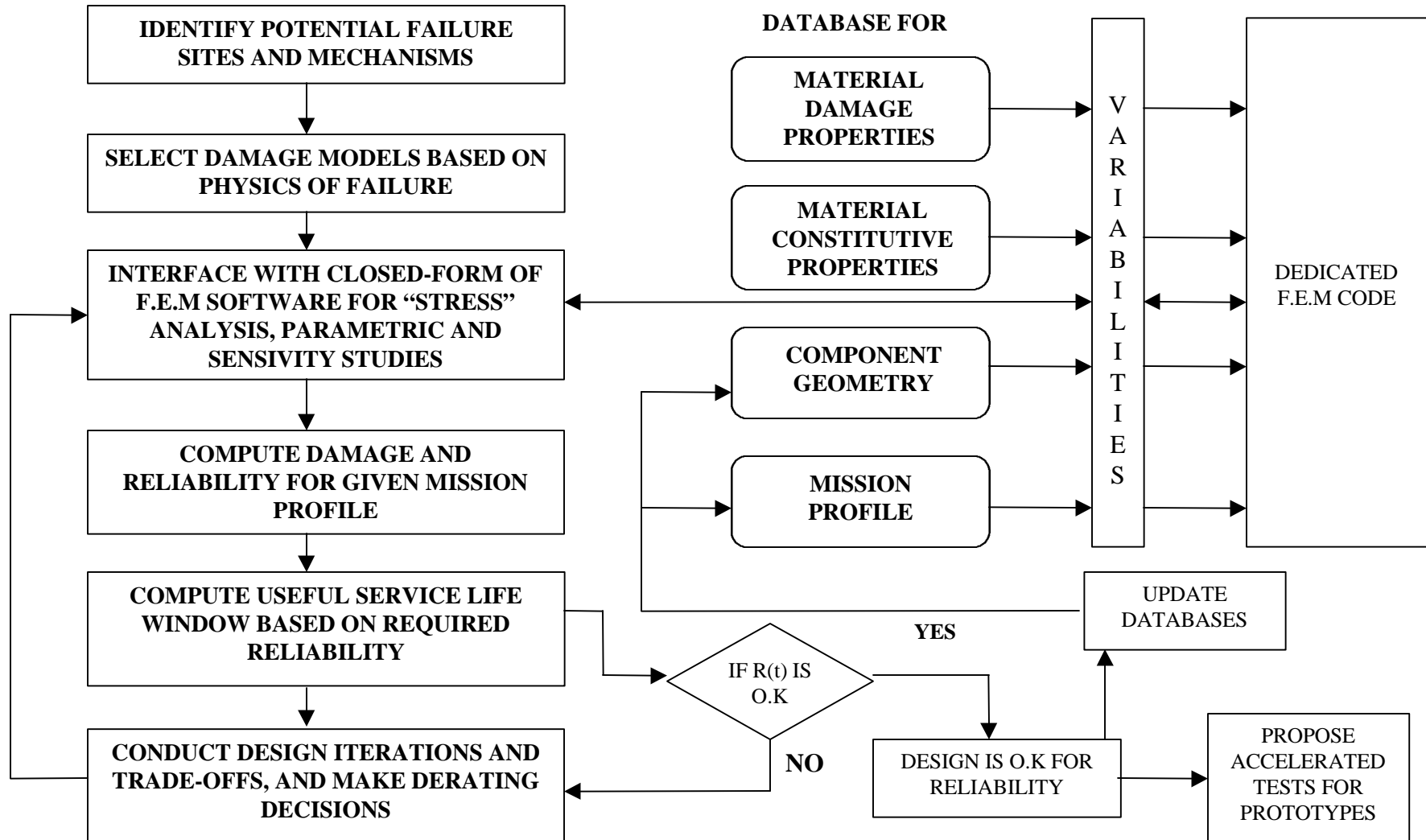|		
Reliability Stress Analysis for Electronic Equipment (TR-1100)	**Nov 1956**	RCA models for computing failure rates
MIL-HDBK-217A	**Dec 1965** Preparing Activity: Navy	Single point failure rate of 0.4 fr/mhr for all monolithic ICs
MIL-HDBK-217B	**July 1973** Preparing Activity: Air Force - Rome Labs	Exponential distribution based models
MIL-HDBK-217C	**April 1979** Preparing Activity: Air Force - Rome Labs	Band-aid for memory. For example when 4k RAM model was extrapolated to 64K MTBF = 13 seconds
MIL-HDBK-217D	**Jan 1982** Preparing Activity: Air Force - Rome Labs	Band-aid. No technical change in format
MIL-HDBK-217E	**Oct 1987** Preparing Activity: Air Force - Rome Labs	Band-aid. No technical change in format
MIL-HDBK-217F	**Dec 1990** Preparing Activity: Air Force - Rome Labs	Band-aid. No technical change in format

Physics of **Failure**
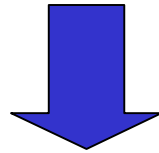
Creating Analytical Models using Underlying Constitutive Relations:
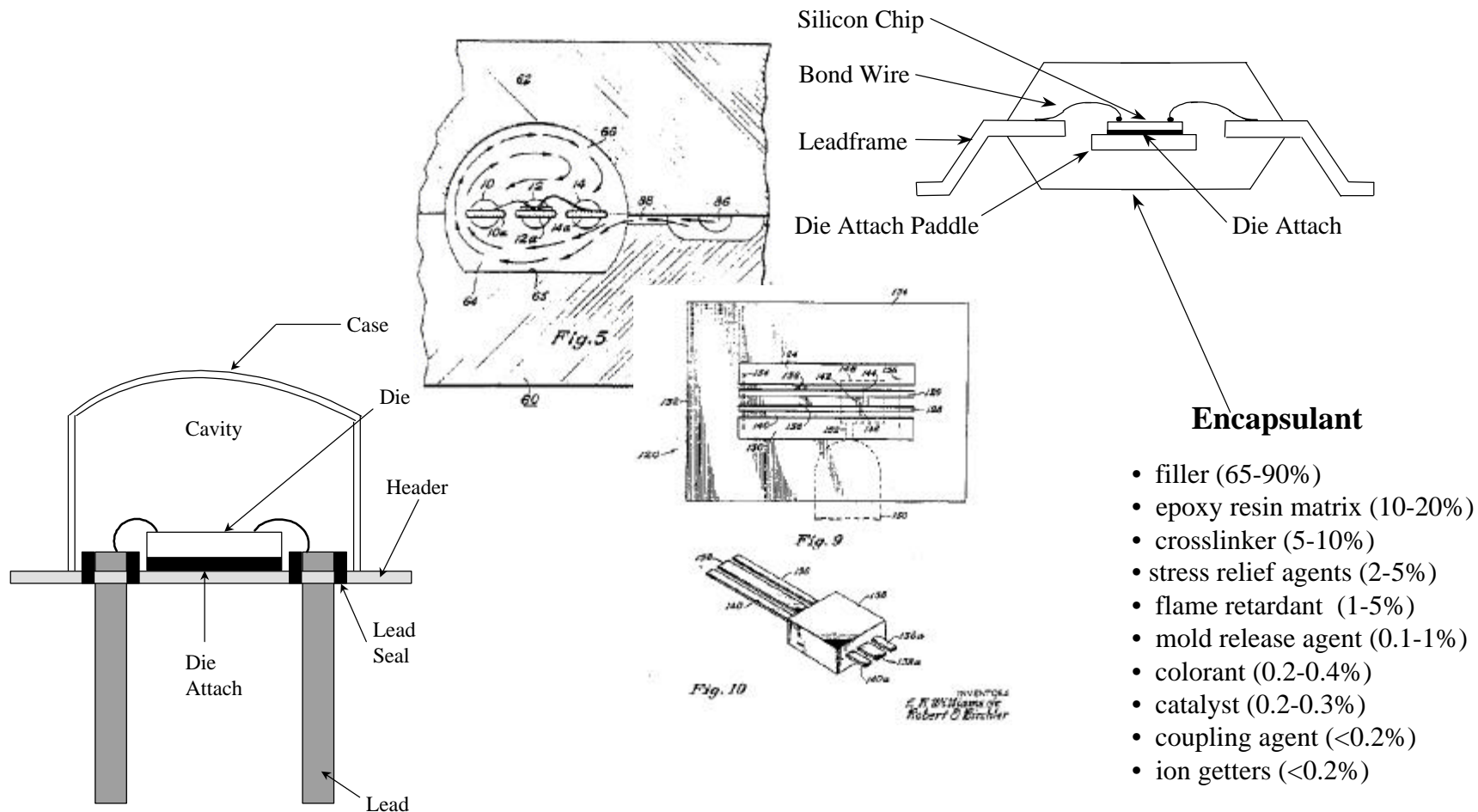
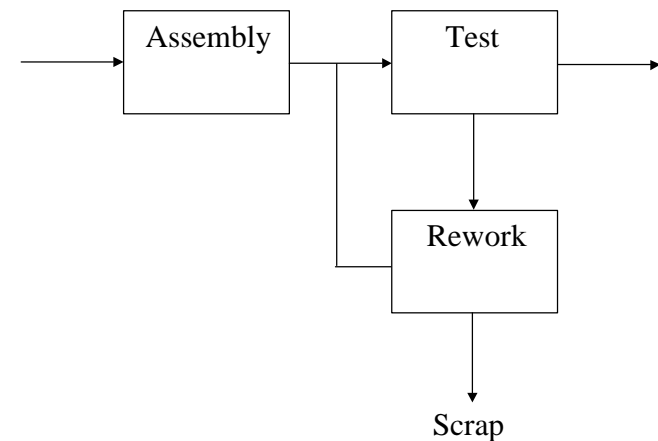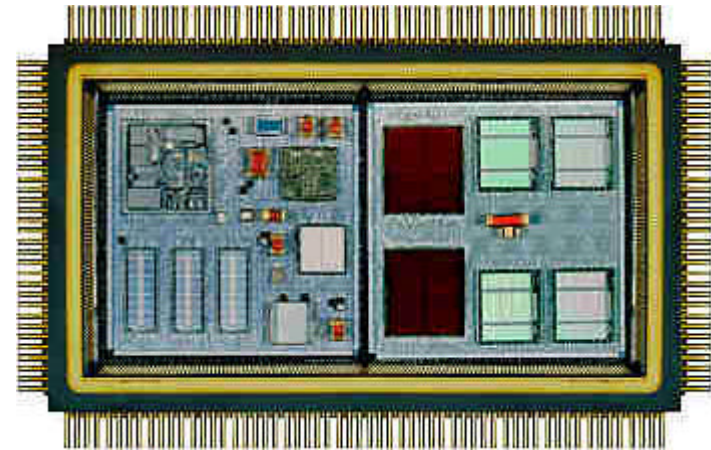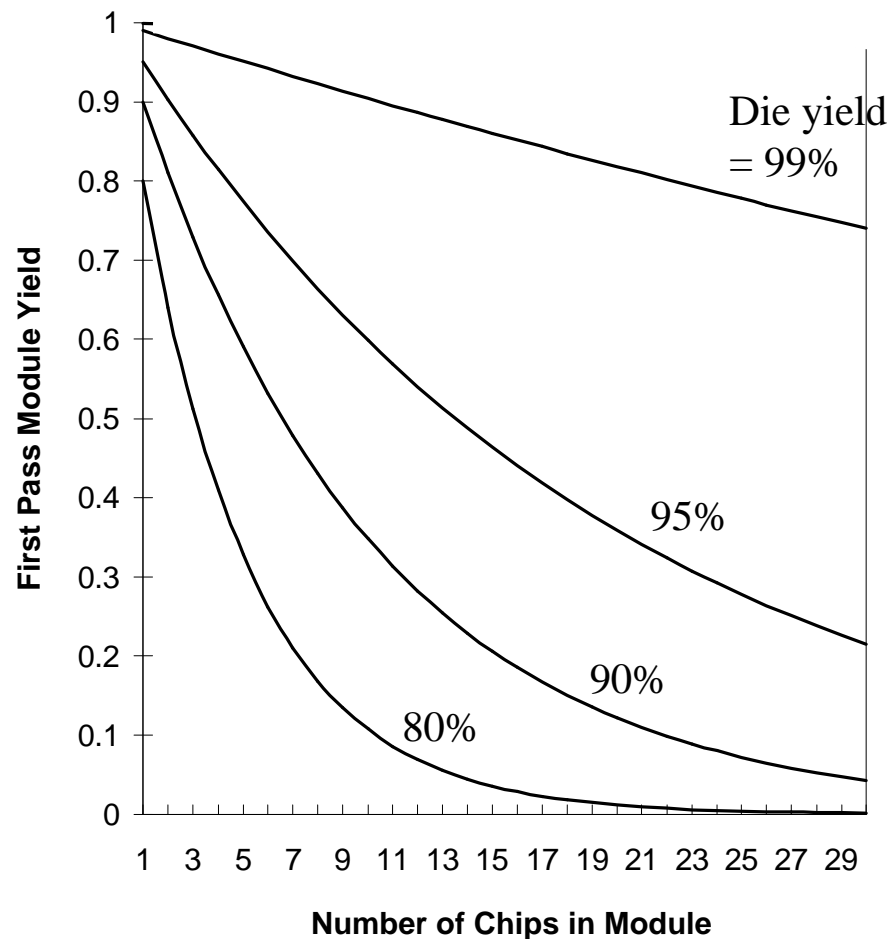*Physical Phenomena*

Physical Failure of Components and Devices

Mechano-Stochastic Failure Analysis Methodology (Circa 1983)

```
┌─────────────────────────────┐
│ IDENTIFY POTENTIAL FAILURE  │
│   SITES AND MECHANISMS      │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ SELECT DAMAGE MODELS BASED ON│
│     PHYSICS OF FAILURE      │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ INTERFACE WITH CLOSED-FORM OF│
│  F.E.M SOFTWARE FOR "STRESS" │
│  ANALYSIS, PARAMETRIC AND    │
│     SENSITIVITY STUDIES      │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│   COMPUTE DAMAGE AND         │
│ RELIABILITY FOR GIVEN MISSION│
│         PROFILE              │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ COMPUTE USEFUL SERVICE LIFE  │
│ WINDOW BASED ON REQUIRED     │
│        RELIABILITY           │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ CONDUCT DESIGN ITERATIONS AND│
│ TRADE-OFFS, AND MAKE DERATING│
│         DECISIONS            │
└─────────────────────────────┘
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DATABASE FOR

- MATERIAL DAMAGE PROPERTIES
- MATERIAL CONSTITUTIVE PROPERTIES
- COMPONENT GEOMETRY
- MISSION PROFILE

VARIABILITIES

DEDICATED F.E.M CODE

IF R(t) IS O.K

YES → UPDATE DATABASES

NO

DESIGN IS O.K FOR RELIABILITY

PROPOSE ACCELERATED TESTS FOR PROTOTYPES

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Single Chip Package Evolution

Silicon Chip

Bond Wire

Leadframe

Die Attach Paddle

Die Attach

Fig.5

Fig. 9

Fig. 10

Case

Die

Cavity

Header

Lead
Seal

Die
Attach

Lead

Encapsulant

- filler (65-90%)
- epoxy resin matrix (10-20%)
- crosslinker (5-10%)
- stress relief agents (2-5%)
- flame retardant (1-5%)
- mold release agent (0.1-1%)
- colorant (0.2-0.4%)
- catalyst (0.2-0.3%)
- coupling agent (<0.2%)
- ion getters (<0.2%)

The Known Good Die (KGD) Problem in the Evolution of Multichip Modules

Die yield = 99%

95%

90%

80%

First Pass Module Yield

Number of Chips in Module

Assembly → Test → Rework → Scrap

Physics of Failure Process

INPUTS

Operational Loads
Power dissipation, voltage, current, and frequency

Environmental Loads
Temperature, relative humidity, pressure, shock and their cyclic ranges, rate of change and time and spatial gradients.
The life cycle includes transportation, storage, handling and application environments

Product materials, geometry, and architecture

Life Cycle Environmental Profiles

Stress Analysis

Thermal
Thermo-mechanical
Radiation
Hygro-mechanical
Electromagnetic
Vibration-shock
Diffusion

Reliability Assessment

Determines appropriate failure mechanism model(s) and calculates time-to-failure for each failure mechanism

Sensitivity Analysis

Evaluate sensitivity of the product life to the application

Define the safe-operating region for the desired life cycle profile

Define potential screening and accelerated test conditions

OUTPUTS

Ranked list of potential failure mechanisms and sites

Design tradeoffs

Stress management solutions

Screening conditions

Accelerated test conditions

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?

Show Stoppers / Bottlenecks

Layout (dynamic component footprint)

Thermal scheduling

KGD

Micro-substrates

Reworkability

Show Stoppers / Bottlenecks

Assembly induced defects

Power-thermal cycling

Hermeticity

PoF Applied to
In2m
(multiple -size, multi -function,
multi -technology domain

?

Multi-Chip Modules
(one size - multi-electronic
technology domain)

PoF Applied to
Components
(one size - one technology
domain)

Few chip
modules

Memory
stacks

Microvia
board
(BGA)

z - axis conductive
adhesives

Flip-chip underfill

PEMs

CSPs

**Increasing Complexity
Decreasing Time to Deployment**

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In2m System Example

Safety & Arming System

Electrical:
• Fire-set
• Actuator drive signals

Physical:
• Hydrostatic Pressure

Optical:
• Independent Position Verification

Explosive Detonation

Lid

Elastomer

Stripline

Top Chip

S&A Chip (bottom chip)

Bond Layer

Carrier

Pressure Inlet

Explosive Pellet

# Problem: What types of thermal management schemes allow integration across varying length scales from μm to mm?

Enhanced structure

Vapor

Metal foam condenser

Condensed liquid

MEMS sensor/ transducer

MCM

Micro pump for gravity independent operation

Microfuel cell

Microfluidic device

In2m module

10 mm

4-6 mm

80 μm

10 mm

<u>Problem:</u> The combination of materials (micro-metrology) and especially the interconnects between In2m subsystem technologies must:

- enable quality manufacture and precipitable defects across sizes
- meet the application reliability needs
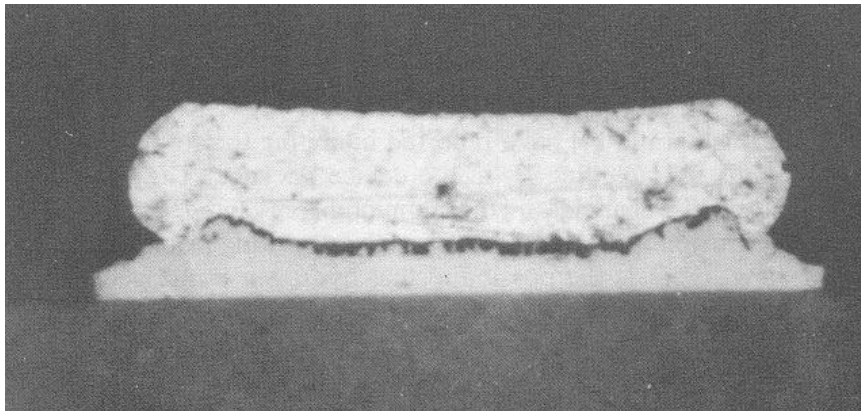
Kirkendall voiding in aluminum-gold interconnect
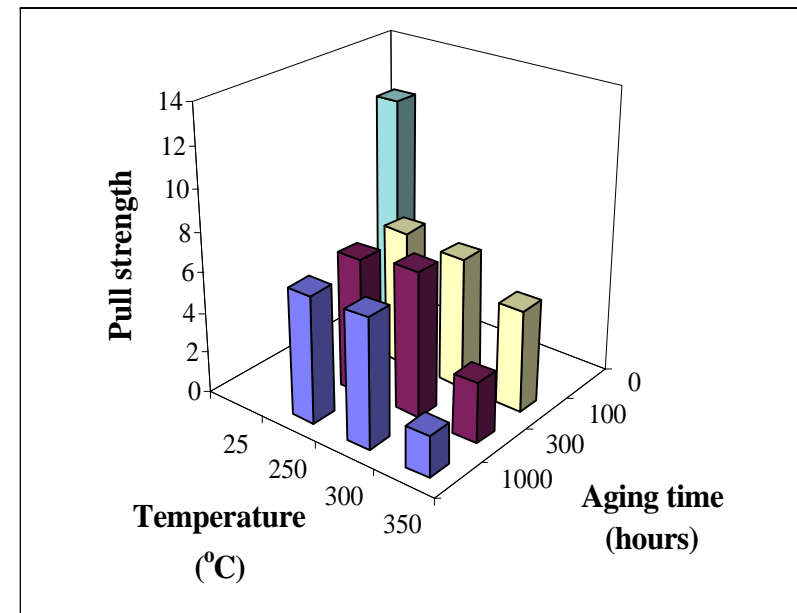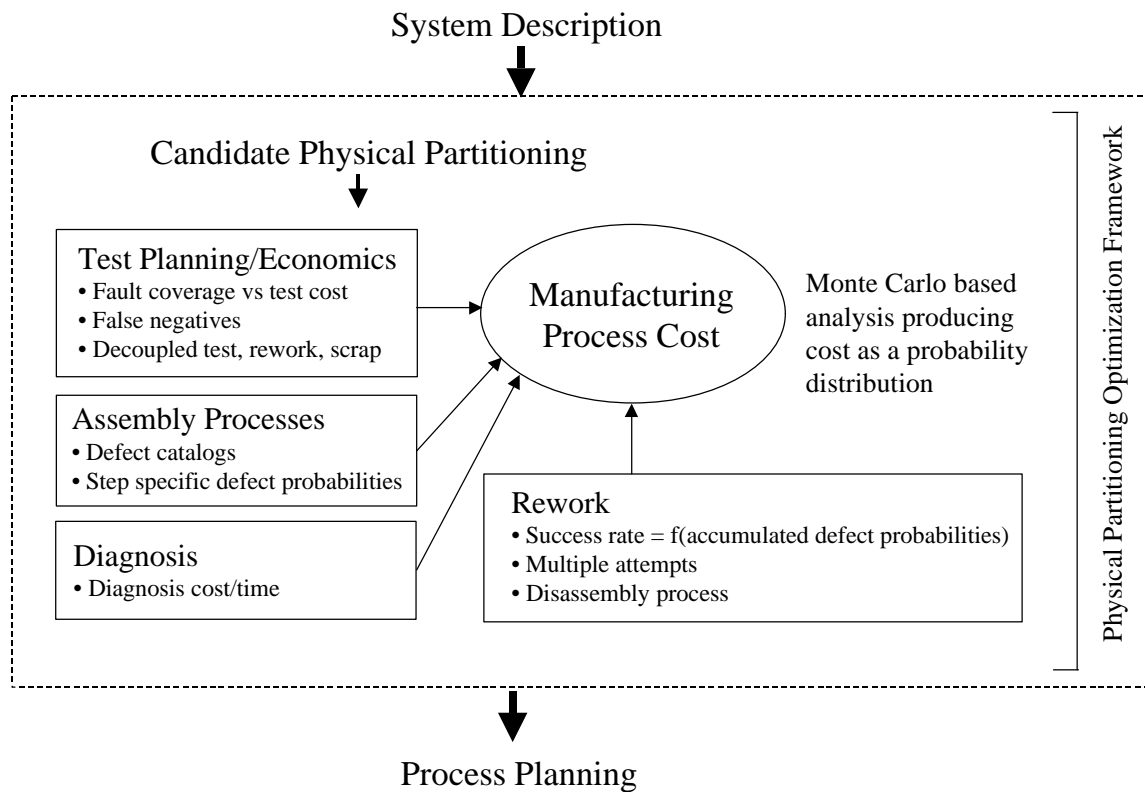

Accompanying loss of strength

<u>Problem:</u> As integration level moves from nano to millimeter, different connection topologies become relevant. Topology determines the number of connection crossovers which in turn drives:

- Design costs
- Assembleability
- Reliability
- Maintainability

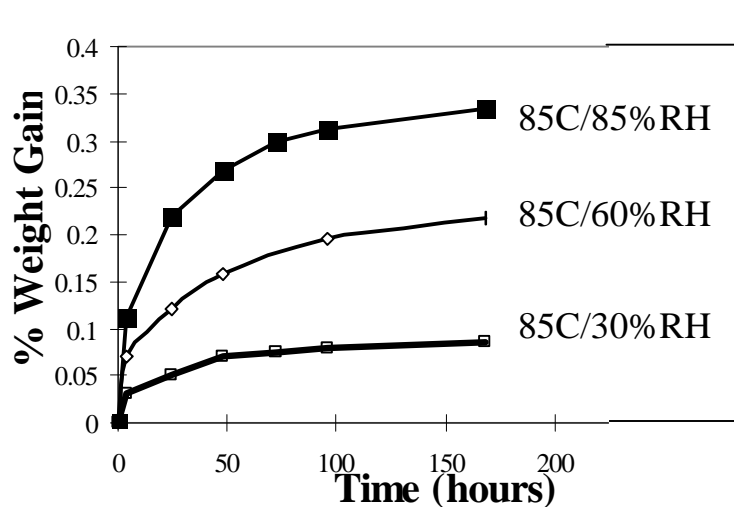| Integration Level	Relavent Connection Topologies
Device to device	Planar
Die to die	Planar Plane-in-plane
Chip to chip	Planar Plane-in-plane
Die to module (MCM)	Plane-in-plane
Chip to board	Plane-in-plane Edge-to-plane
Module to board	Plane-in-plane Edge-to-plane
Board to board	Plane-in-plane Edge-to-plane Edge-to-edge
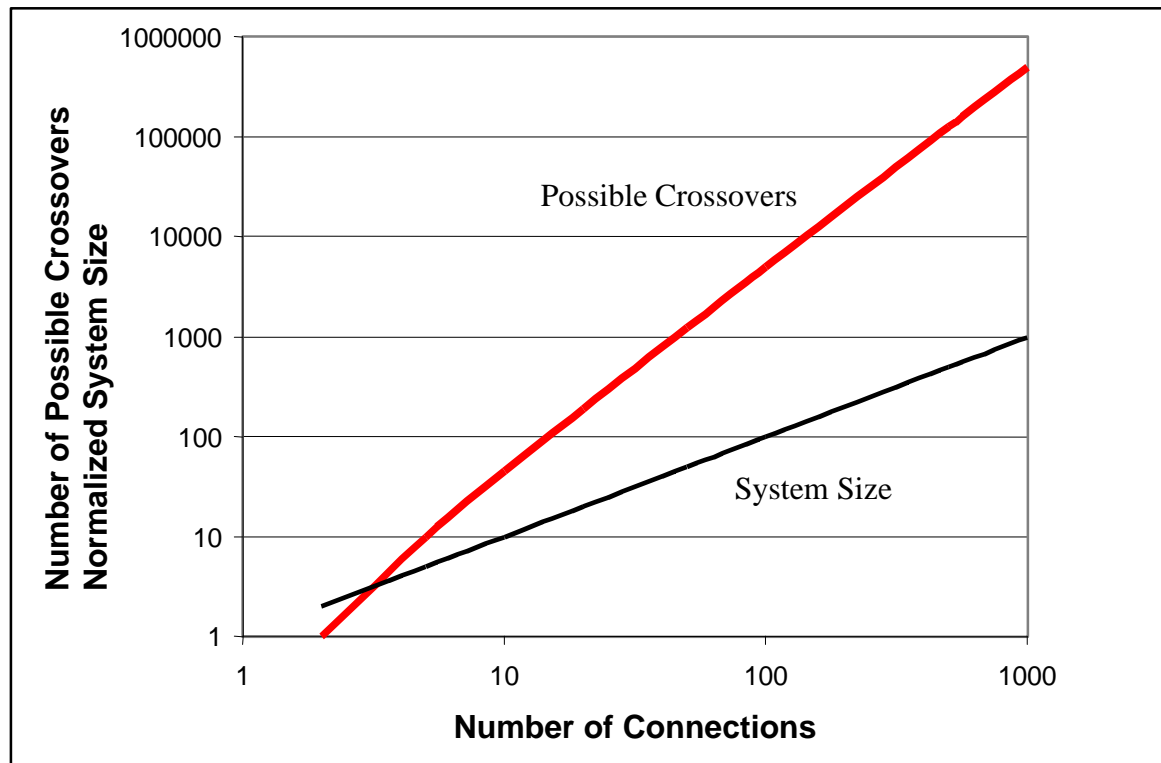
Problem: How can systems composed of many dissimilar components be physically partitioned to minimize a combination of assembly, test, and rework costs?
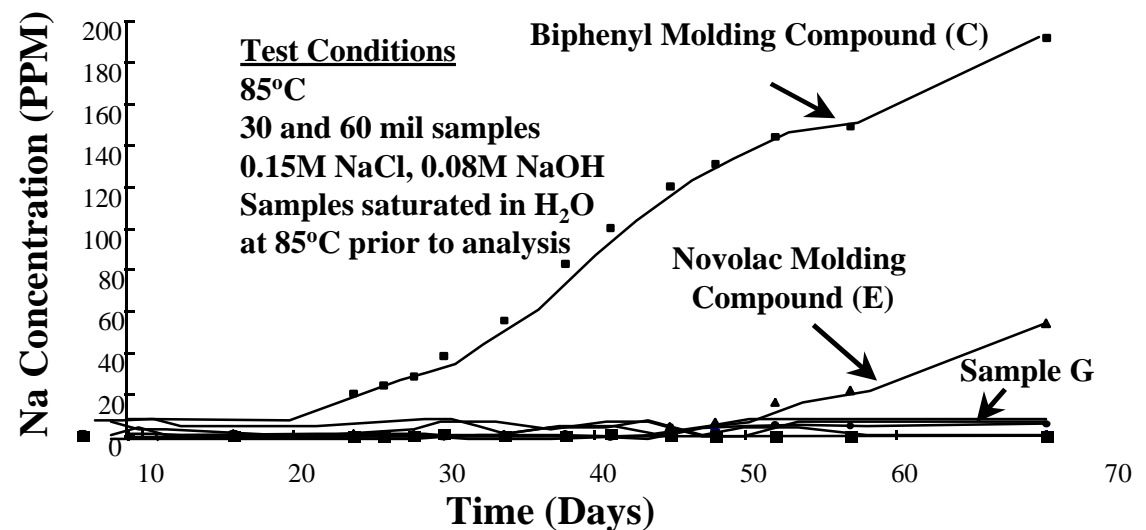
System Description

Candidate Physical Partitioning

Test Planning/Economics
- Fault coverage vs test cost
- False negatives
- Decoupled test, rework, scrap

Assembly Processes
- Defect catalogs
- Step specific defect probabilities

Diagnosis
- Diagnosis cost/time

Manufacturing Process Cost

Monte Carlo based analysis producing cost as a probability distribution

Rework
- Success rate = f(accumulated defect probabilities)
- Multiple attempts
- Disassembly process

Physical Partitioning Optimization Framework

Physical Partitioning = distributing components throughout the "packaging hierarchy" (i.e., amongst packages, boards, modules and boxes)

Process Planning

Problem: The packaging of the system must

- provide environmental protection
- enable connectings to other system
- not interfere with the operation of the system


Moisture Absorption in Epoxy Novalac

(chart: % Weight Gain vs Time (hours); curves labeled 85C/85%RH, 85C/60%RH, 85C/30%RH)

Ionic Diffusion

(chart: Na Concentration (PPM) vs Time (Days))

Test Conditions
85ºC
30 and 60 mil samples
0.15M NaCl, 0.08M NaOH
Samples saturated in H$_2$O
at 85ºC prior to analysis

Biphenyl Molding Compound (C)

Novolac Molding Compound (E)

Sample G

Problem: There is a need to qualify a system for the target application effectively and efficiently

Virtual Qualification

Information
- Supplier
- Revision Date
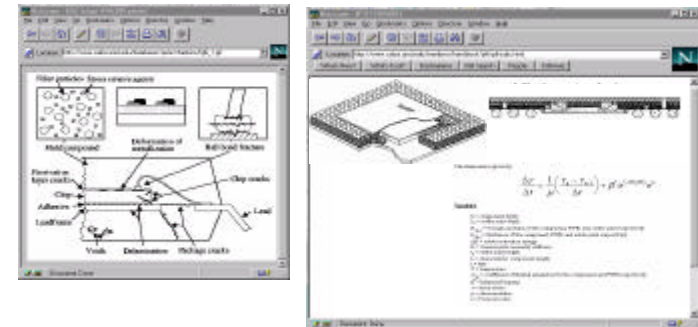
Product Information

Mentor
PADS
Protel
Zuken-Recal
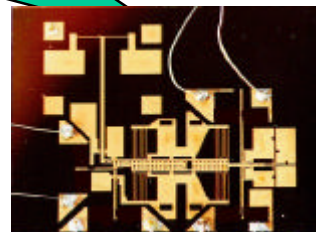AutoCAD

Electronic Data

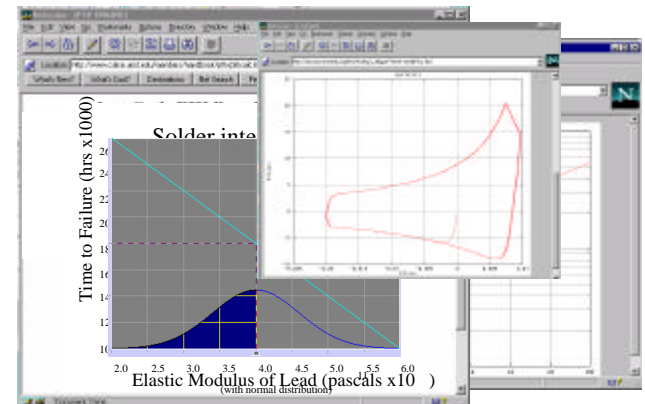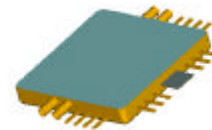Data entry and viewing is based on user access level. (suppliers may be limited to their own products)

Authentication restricts software and information to registered users

Internet or Intranet

Time to Failure (hrs x1000)

Solder inte...

Elastic Modulus of Lead (pascals x10)
(with normal distribution)

Expert consultation

Product modeling

Product analysis

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